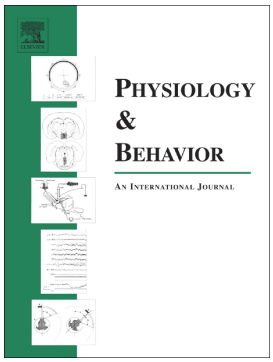
An integrative perspective of the anaerobic threshold

Sales, Marcelo Magalhães ; Sousa, Caio Victor ; da Silva Aguiar, Samuel ; Knechtle, Beat ; Nikolaidis, Pantelis Theodoros ; Alves, Polissandro Mortoza ; Simões, Herbert Gustavo

Abstract: The concept of anaerobic threshold (AT) was introduced during the nineteen sixties. Since then, several methods to identify the anaerobic threshold (AT) have been studied and suggested as novel 'thresholds' based upon the variable used for its detection (i.e. lactate threshold, ventilatory threshold, glucose threshold). These different techniques have brought some confusion about how we should name this parameter, for instance, anaerobic threshold or the physiological measure used (i.e. lactate, ventilation). On the other hand, the modernization of scientific methods and apparatus to detect AT, as well as the body of literature formed in the past decades, could provide a more cohesive understanding over the AT and the multiple physiological systems involved. Thus, the purpose of this review was to provide an integrative perspective of the methods to determine AT.

DOI: https://doi.org/10.1016/j.physbeh.2017.12.015

Accepted Manuscript



An integrative perspective of the anaerobic threshold

Marcelo Magalhães Sales, Caio Victor de Sousa, Samuel da Silva Aguiar, Beat Knechtle, Pantelis Theodoros Nikolaidis, Polissandro Mortoza Alves, Herbert Gustavo Simões

PII: S0031-9384(17)30437-7
DOI: doi:10.1016/j.physbeh.2017.12.015
Reference: PHB 12009

To appear in: *Physiology & Behavior*

Received date: 27 October 2017
Revised date: 13 December 2017
Accepted date: 13 December 2017

Please cite this article as: Marcelo Magalhães Sales, Caio Victor de Sousa, Samuel da Silva Aguiar, Beat Knechtle, Pantelis Theodoros Nikolaidis, Polissandro Mortoza Alves, Herbert Gustavo Simões , An integrative perspective of the anaerobic threshold. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Phb(2017), doi:10.1016/j.physbeh.2017.12.015

PERSPECTIVE / NARRATIVE REVIEW

AN INTEGRATIVE PERSPECTIVE OF THE ANAEROBIC THRESHOLD

Marcelo Magalhães Sales[1]*, Caio Victor de Sousa[2,*,✉], Samuel da Silva Aguiar[2], Beat Knechtle[3,4], Pantelis Theodoros Nikolaidis[5], Polissandro Mortoza Alves[1], Herbert Gustavo Simões[2]

[1]UniversidadeEstadual de Goiás, Quirinópolis, Goiás, Brazil; [2]Graduate Program in Physical Education, Universidade Católica de Brasília, Distrito Federal, Brazil; [3]Gesundheitszentrum St. Gallen, St. Gallen, Switzerland; [4]Institute of Primary Care, University of Zurich, Zurich, Switzerland; [5]Exercise Physiology Laboratory, Nikaia, Greece; *These authors have contributed equally to this work.

Corresponding author (✉)

Name: Caio Victor de Sousa

Mailling address: Universidade Católica de Brasília – UCB, Brasília DF, Brazil.

EPTC, QS07, LT1 s/n. Bloco G Sala 15. Postal code: 72030-170

Taguatinga/DF-Brazil.

Telephone/Fax: +55 (61) 3356 9350

E-mail: cvsousa89@gmail.com

ABSTRACT

The concept of anaerobic threshold (AT) was introduced during the nineteen sixties. Since then, several methods to identify the anaerobic threshold (AT) have been studied and suggested as novel 'thresholds' based upon the variable used to detect it (i.e. lactate threshold, ventilatory threshold). These different techniques have brought some confusion about how we should name this parameter, for instance, anaerobic threshold or the physiological measure used(i.e. lactate, ventilation). On the other hand, the modernization of scientific apparatus and methods, as well as the body of literature formed in the past decades, could provide a more cohesive understanding over the AT and the multiple physiological systems involved. Thus, the purpose of this review was to provide an integrative perspective of the methods to determine AT.

Keywords: Aerobic exercise; Autonomic Nervous System; Catecholamines; Heart rate; Blood pressure; Blood glucose; Lactate; Ventilation.

1 INTRODUCTION

The historical concept of the anaerobic threshold (AT) can be idealized as an exercise intensity below which there is an increased contribution of energy associated with metabolic acidosis and consequently respiratory compensation [1, 2]. This concept was initially proposed by Wasserman and McIlroy in 1964, after conducting a study that aimed to identify an exercise intensity that provided a substantial, but safe, amount of physical stress for patients suffering from cardiovascular disease [3]. During that time, the metabolic acidosis provided by vigorous exercise was seen as a risk for those patients. Nowadays, the AT is considered a hallmark of scientific research, aerobic fitness [3-5] and is a widely used parameter for exercise prescription [6, 7].

Over the years, several methods to identify the AT have been studied and suggested as novel 'thresholds' based upon the variable used to detect it (i.e. lactate threshold, ventilatory threshold). These different techniques have brought some confusion about how we should name this parameter: for instance, anaerobic threshold or the physiological measure used, i.e. lactate, ventilation[3]. Nevertheless, the modernization of scientific apparatus and methods as well as the body of literature formed in the past decades could provide a more cohesive understanding over the AT and the multiple physiological systems involved. Therefore, the aim of this review is to provide an integrative perspective of the methods to determine AT.

2 PHYSIOLOGICAL ENGINE

2.1 Peripheral Stimuli and Autonomic Adjustment

Exercise is accompanied by a well-established increase in sympathetic activity and reduction in parasympathetic activity in regions that together increase heart rate, stroke volume and therefore cardiac output, facilitating the redistribution of blood flow to the active

skeletal muscles [8]. Such autonomic responses to exercise are triggered by the interactions of several central and peripheral neural mechanisms. The parallel activation of somatomotorcentres (SMC) and *nucleus tractussolitarii* (NTS), referred to as 'central command', provides a feedforward coupling of skeletal muscle contraction and adjustments in cardiovascular control [9].

Central command (CC) is traditionally viewed as mediating the increase in heart rate at the onset exercise [10]. Peripheral stimuli are conducted via appropriate afferents, including skeletal muscle mechanoreceptors and metabolically sensitive skeletal muscle afferents fibers (muscle metaboreflex) to the NTS, ascending from there to higher integrative areas in the central nervous system, such as the paraventricular nucleus of the hypothalamus [11, 12].

In addition, afferent fibers carrying information from the skeletal muscles make excitatory synaptic contact with the GABAergic interneurons in the NTS, which in turn transmit signals to the nerve cells in the caudal ventral lateral medulla (CVLM) via excitatory glutamatergic synapses. The output of the CVLM provides the main inhibitory (GABAergic) inputs to the cardiovascular sympathetic neurons in the rostral ventral lateral medulla (RVLM), the main output neurons that regulate sympathetic nerve activity [13, 14]. Together with skeletal muscle afferents, arterial and cardiorespiratory baroreceptors also send inputs to the CC that may influence autonomic response during exercise [15].

Integration of afferent signals within the brain stem results in efferent parasympathetic and sympathetic outflow. At sub-AT stages of exercise, efferent sympathetic activity to the heart, adrenal gland and blood vessels increases gradually and linearly to the imposed workload concomitant to a gradual parasympathetic withdraw [16, 17] to maintain cardiac output and others metabolic demands. Then, at 60 – 80% of VO_2max generally occur total withdraw of parasympathetic tonus followed by a substantial increase in sympathetic activity [19]. At this point, autonomic modulation in the heart seems to completely stop by the

parasympathetic withdrawal, what is perceived in heart rate variability (HRV) cessation, characterized as the HRV threshold [19, 20].

2.2 Neuroendocrine Response

The viscero-somatosensory stress stimuli in CC generates efferent outflow from the brain back to the periphery via two hormonal systems: (1) the hypothalamus-pituitary-adrenal axis (HPA), which releases adrenocorticotrophic hormone from the pituitary gland into the bloodstream, resulting in an increase in circulating glucocorticoids like cortisol secreted from the adrenal cortex; (2) brainstem catecholaminergic neurons and spinal cord efferents in the interomedial lateral column, which converge on preganglionic sympathetic neurons to activate the sympathetic nervous system and adrenal medulla, increasing circulating norepinephrine (NE) and epinephrine (Epi) [21, 22].

Circulating Epi is derived from the adrenal chromaffin cells located in the adrenal medulla. These cells are in many ways similar to a sympathetic postganglionic neuron, but instead of innervating specific target organs, they secrete their vesicular contents into the bloodstream [21]. During physical stress (i.e. exercise test) sympathetic nervous system is rapidly stimulated, leading to large increases in the secretion of Epi and NE from the adrenal chromaffin cells. These increases are needed to produce the changes in the function of the visceral organs, smooth muscles and glands, which are required to adapt to the instantaneous stress environment. During a physical activity situation, for instance, one of the major aims may be to maintain the supply of energy and O_2 in the active muscles [21-23].

Therefore, total parasympathetic withdraw at certain intensity of exercise may cause hyperactivity in adrenal medulla and substantially increase circulating Epi and NE, marking the catecholamine threshold [24, 25].

2.3 Hemodynamic and Metabolic Effects

During exercise the major effect of Epi and NE is to redistribute the blood flow from the kidneys, gastrointestinal tract, and skin to dilating vessels in the skeletal muscles. Moreover, both Epi and NE are powerful cardiac stimulants. It increases heart rate (HR) and the force of myocardial contraction (chronotropism and inotropism).

These effects are primarily mediated adrenergic receptors (Ars) accelerating heart rate by acting directly on pacemaker cells of the sinoatrial (SA) and atrioventricular nodes, as well as the conducting Purkinje fibers [26, 27]. During a progressive exercise test, the gradual enhancement of Epi and NE undergo a substantial increase at 60 – 80% of VO_2max [24] and the cardiovascular consequence is a considerable rise in HR and peripheral vascular resistance (PVR) and consequently systolic blood pressure (SBP), causing a disproportionate rise in double product (DP), becoming the heart rate threshold [28, 29] and double-product threshold [23, 30-32] respectively.

Circulating Epi also produces large increases in blood levels of glucose and free fatty acids as well as energy substrates for skeletal muscles, heart and brain during a sympathetic response like exercising [33]. Thus, blood glucose that tends to reduce during an incremental exercise test gets to a breakpoint and starts to rise, characterizing the glycemic threshold [5]. The rise in glucose may be due to inhibition of insulin secretion by an interaction ARs in the pancreas and increased glycogenolysis in most tissues, especially in the liver [21, 33].

At this point of progressive exercise, oxygen delivery to the tissues by the oxidative system may not account for all the energy use by the muscles. To ensure a continued supply of NAD^+ for glycolysis through NADH oxidation, pyruvate resulting from anaerobic glycolysis is converted to lactate instead of being incorporated into oxidative metabolism[34, 35], and its accumulation characterizes the lactate threshold (LT). This is very clearly described in an elegant review article by Svedahl and MacIntosh [3].

The accumulation of lactate and high intramuscular hydrogen levels can modify the coupling of excitation-contraction of muscles assets, including properties of the muscle membrane and propagation of the action potential, leading to a decrease in strength and contractility [36, 37]. Thus, to compensate for the situation of acidosis during incremental exercise, there should be the recruitment of additional motor units with possible participation of type IIa and IIb fibers respectively, showing a nonlinear increase (breakpoint) in electromyographic activity [38]and characterizing the electromyographic threshold (EMGT) [39, 40]. Although EMGT highly correlates with LT and VT, it does not necessarily coincide, since the EMGT occurs between 80 and 92% of VO_2max [38, 40].

2.4 Metabolic and Gas Exchange Dynamics

Moreover, catecholamines have two major effects on the lungs: (1) a decrease in fluid secretion from bronchial glands, mediated by αAR; and (2) they relax bronchial smooth muscles, mediated by βAR [33]. Further, Epi has a particular and powerful bronchodilator effect, leading to increased O_2 uptake and therefore high production of CO_2, resulting in a disproportional rise in ventilation (VE) versus workload, known as the ventilatory threshold (VT) [41, 42].

FIGURE 1 HERE

3 FINAL CONSIDERATIONSANDAPPLICATIONS

In conclusion, AT may be summarized as a single physiological event. However, the development of new methods was important in strengthening the physiological theory that supports the event in question. Moreover, the opposite is also true, since the theory allowed researchers within this field of knowledge to investigate the validity of new markers and with more practical applications, facilitating broad access to coaches, athletes and groups such as

diabetics, those with hypertension and the elderly. Future research should focus on training sensitivity of the testing methods, since all the physiological systems involved may adapt in different timings providing distinct responses after exercise training.

FIGURE 2 HERE

As a practical application, this perspective suggests that regardless of the method used, all seem to identify the AT at the same point or very close. This finding is of great practical importance from many perspectives (e.g. invasive methods, financial cost) for professionals measuring and evaluating AT in the context of exercise testing and training. For instance, the use of the ventilatory equivalent for O_2 (i.e. the ratio of minute ventilation to VO_2) requires only an O_2 gas analyzer and such equipment is less expensive than the equipment consisting of both O_2 and CO_2 gas analyzers, which are needed for the assessment of respiratory exchange ratio. Furthermore, using invasive methods (e.g. blood lactate sampling) for exercise testing in specific populations such as children is not recommended. Since AT is identified similarly independently from the method, in such populations non-invasive methods such as those based on respiratory parameters should be recommended. Thus, we suggest to professionals using any equipment capable of measuring some of the variables involved in the physiological event in question that, based on the theory, these can be identified without any problems.

REFERENCES

[1] K. Wasserman, B.J. Whipp, S.N. Koyl, W.L. Beaver. Anaerobic threshold and respiratory gas exchange during exercise. Journal of applied physiology. 1973,35:236-43.
[2] J.A. Davis, P. Vodak, J.H. Wilmore, J. Vodak, P. Kurtz. Anaerobic threshold and maximal aerobic power for three modes of exercise. Journal of applied physiology. 1976,41:544-50.
[3] K. Svedahl, B.R. MacIntosh. Anaerobic threshold: the concept and methods of measurement. Canadian journal of applied physiology = Revue canadienne de physiologie appliquee. 2003,28:299-323.

[4] H.G. Simoes, W.C. Hiyane, R.E. Benford, B. Madrid, F.A. Prada, S.R. Moreira, et al. Lactate threshold prediction by blood glucose and rating of perceived exertion in people with type 2 diabetes. Perceptual and motor skills. 2010,111:365-78.
[5] H.G. Simoes, C.S. Campbell, M.R. Kushnick, A. Nakamura, C.S. Katsanos, V. Baldissera, et al. Blood glucose threshold and the metabolic responses to incremental exercise tests with and without prior lactic acidosis induction. European journal of applied physiology. 2003,89:603-11.
[6] P.K. Morais, C.S. Campbell, M.M. Sales, D.F. Motta, S.R. Moreira, V.N. Cunha, et al. Acute resistance exercise is more effective than aerobic exercise for 24h blood pressure control in type 2 diabetics. Diabetes & metabolism. 2011,37:112-7.
[7] P.K. Morais, M.M. Sales, J. Alves de Almeida, D. Motta-Santos, C.V. Sousa, H.G. Simoes. Effects of aerobic exercise intensity on 24-h ambulatory blood pressure in individuals with type 2 diabetes and prehypertension. Journal of physical therapy science. 2015,27:51-6.
[8] J.H. Mitchell. J.B. Wolffe memorial lecture. Neural control of the circulation during exercise. Medicine and science in sports and exercise. 1990,22:141-54.
[9] G.M. Goodwin, D.I. McCloskey, J.H. Mitchell. Cardiovascular and respiratory responses to changes in central command during isometric exercise at constant muscle tension. The Journal of physiology. 1972,226:173-90.
[10] A. Krogh, J. Lindhard. A comparison between voluntary and electrically induced muscular work in man. The Journal of physiology. 1917,51:182-201.
[11] J.P. Fisher. Autonomic control of the heart during exercise in humans: role of skeletal muscle afferents. Experimental physiology. 2014,99:300-5.
[12] L.C. Michelini, D.S. O'Leary, P.B. Raven, A.C. Nobrega. Neural control of circulation and exercise: a translational approach disclosing interactions between central command, arterial baroreflex, and muscle metaboreflex. American journal of physiology. Heart and circulatory physiology. 2015,309:H381-92.
[13] J.T. Potts. Inhibitory neurotransmission in the nucleus tractus solitarii: implications for baroreflex resetting during exercise. Experimental physiology. 2006,91:59-72.
[14] C.Y. Chen, A.C. Bonham. Postexercise hypotension: central mechanisms. Exercise and sport sciences reviews. 2010,38:122-7.
[15] J.P. Fisher, C.N. Young, P.J. Fadel. Autonomic adjustments to exercise in humans. Comprehensive Physiology. 2015,5:475-512.
[16] M.P. Tulppo, T.H. Makikallio, T.E. Takala, T. Seppanen, H.V. Huikuri. Quantitative beat-to-beat analysis of heart rate dynamics during exercise. The American journal of physiology. 1996,271:244-52.
[17] O. Anosov, A. Patzak, Y. Kononovich, P.B. Persson. High-frequency oscillations of the heart rate during ramp load reflect the human anaerobic threshold. European journal of applied physiology. 2000,83:388-94.
[18] M.P. Tulppo, T.H. Makikallio, T. Seppanen, R.T. Laukkanen, H.V. Huikuri. Vagal modulation of heart rate during exercise: effects of age and physical fitness. The American journal of physiology. 1998,274:H424-9.
[19] G.K. Karapetian, H.J. Engels, R.J. Gretebeck. Use of heart rate variability to estimate LT and VT. International journal of sports medicine. 2008,29:652-7.
[20] M.M. Sales, C.S. Campbell, P.K. Morais, C. Ernesto, L.F. Soares-Caldeira, P. Russo, et al. Noninvasive method to estimate anaerobic threshold in individuals with type 2 diabetes. Diabetology & metabolic syndrome. 2011,3:1.
[21] A.W. Tank, D. Lee Wong. Peripheral and central effects of circulating catecholamines. Comprehensive Physiology. 2015,5:1-15.
[22] A.V. Edwards, C.T. Jones. Autonomic control of adrenal function. Journal of anatomy. 1993,183 (Pt 2):291-307.

[23] M. Riley, K. Maehara, J. Porszasz, M.P. Engelen, T.J. Bartstow, H. Tanaka, et al. Association between the anaerobic threshold and the break-point in the double product/work rate relationship. European journal of applied physiology and occupational physiology. 1997,75:14-21.
[24] R.S. Mazzeo, P. Marshall. Influence of plasma catecholamines on the lactate threshold during graded exercise. Journal of applied physiology. 1989,67:1319-22.
[25] A. Weltman, C.M. Wood, C.J. Womack, S.E. Davis, J.L. Blumer, J. Alvarez, et al. Catecholamine and blood lactate responses to incremental rowing and running exercise. J Appl Physiol (1985). 1994,76:1144-9.
[26] R.P. Xiao, W. Zhu, M. Zheng, C. Cao, Y. Zhang, E.G. Lakatta, et al. Subtype-specific alpha1- and beta-adrenoceptor signaling in the heart. Trends in pharmacological sciences. 2006,27:330-7.
[27] O.E. Brodde, H. Bruck, K. Leineweber. Cardiac adrenoceptors: physiological and pathophysiological relevance. Journal of pharmacological sciences. 2006,100:323-37.
[28] P. Hofmann, V. Bunc, H. Leitner, R. Pokan, G. Gaisl. Heart rate threshold related to lactate turn point and steady-state exercise on a cycle ergometer. European journal of applied physiology and occupational physiology. 1994,69:132-9.
[29] F. Wyatt, S. Godoy, L. Autrey, J. McCarthy, J. Heimdal. Using a logarithmic regression to identify the heart-rate threshold in cyclists. Journal of strength and conditioning research / National Strength & Conditioning Association. 2005,19:838-41.
[30] H. Tanaka, A. Kiyonaga, Y. Terao, K. Ide, M. Yamauchi, M. Tanaka, et al. Double product response is accelerated above the blood lactate threshold. Medicine and science in sports and exercise. 1997,29:503-8.
[31] K. Omiya, H. Itoh, N. Harada, T. Maeda, A. Tajima, K. Oikawa, et al. Relationship between double product break point, lactate threshold, and ventilatory threshold in cardiac patients. European journal of applied physiology. 2004,91:224-9.
[32] C.V. Sousa, M.M. Sales, S.S. Aguiar, D.A. Boullosa, T.S. Rosa, V. Baldissera, et al. Double product break point estimates ventilatory threshold in individuals with type 2 diabetes. Journal of physical therapy science. 2016,28:1775-80.
[33] T.C. Westfall, D.P. Westfall. Neurotransmission: the autonomic and somatic motor nervous systems. Goodman and Gilman's The Pharmacological Basis of Therapeutics. 2006,167.
[34] G.A. Brooks. Intra- and extra-cellular lactate shuttles. Medicine and science in sports and exercise. 2000,32:790-9.
[35] G.A. Brooks, H. Dubouchaud, M. Brown, J.P. Sicurello, C.E. Butz. Role of mitochondrial lactate dehydrogenase and lactate oxidation in the intracellular lactate shuttle. Proceedings of the National Academy of Sciences of the United States of America. 1999,96:1129-34.
[36] T. Moritani, Y. Yoshitake. 1998 ISEK Congress Keynote Lecture: The use of electromyography in applied physiology. Journal of Electromyography and Kinesiology. 1998,8:363-81.
[37] C.T. Candotti, J.F. Loss, O. Melo Mde, M. La Torre, M. Pasini, L.A. Dutra, et al. Comparing the lactate and EMG thresholds of recreational cyclists during incremental pedaling exercise. Canadian journal of physiology and pharmacology. 2008,86:272-8.
[38] O. Tikkanen, M. Hu, T. Vilavuo, P. Tolvanen, S. Cheng, T. Finni. Ventilatory threshold during incremental running can be estimated using EMG shorts. Physiological measurement. 2012,33:603-14.
[39] F. Hug, D. Laplaud, A. Lucia, L. Grelot. EMG threshold determination in eight lower limb muscles during cycling exercise: a pilot study. International journal of sports medicine. 2006,27:456-62.

[40] F. Hug, M. Faucher, N. Kipson, Y. Jammes. EMG signs of neuromuscular fatigue related to the ventilatory threshold during cycling exercise. Clinical physiology and functional imaging. 2003,23:208-14.
[41] K. Wasserman. Determinants and detection of anaerobic threshold and consequences of exercise above it. Circulation. 1987,76:VI29-39.
[42] B.J. Whipp. Physiological mechanisms dissociating pulmonary CO2 and O2 exchange dynamics during exercise in humans. Experimental physiology. 2007,92:347-55.

FIGURE CAPTIONS

Figure 1. Schematic representation of the physiological engine during anaerobic threshold. Increased sympathetic activity in *nucleus tractus solitaries* leads to in an elevated secretion of adrenal hormones and both increases the heart rate and blood pressure; epinephrine also increases glycogenolysis and consequently elevated glycaemia, leading to increased glucose use in skeletal muscles; the exacerbated production of anaerobic glycolisys metabolites (H^+, lactate, CO_2) input into respiratory centers, which increases ventilation. NTS: *nucleus tractus solitaries*; RC: respiratory centers; HR: heart rate; HRVT: HR variability threshold; HRT: HR threshold; NE: norepinephrine; Epi: epinephrine; CT: catecholamines threshold; VC: vasoconstriction; BP: blood pressure; DP: double-product; DPT: DP threshold; DPBP: DP breakpoint; GLUC: glucose; GT: glucose threshold; LT: lactate threshold; VE: ventilation; VT: ventilatory threshold.

Figure 2. Schematic representation of some physiological variables used to identify the anaerobic threshold during incremental exercise testing. RMSSD (vagal indicator of heart rate variability) - square root of the mean squared successive differences between adjacent R-R intervals; SD1 (vagal indicator of heart rate variability) – instantaneous variability of beat to beat; Gluc – blood glucose; [lac] – blood lactate concentration; VE – ventilation; VE/VO_2– ventilatory equivalents of O_2; VE/VCO_2 - ventilatory equivalents of CO_2; CT – catecholamines threshold; DPBP – double product break point; GT – blood glucose threshold; LT – lactate threshold.

Figure 1

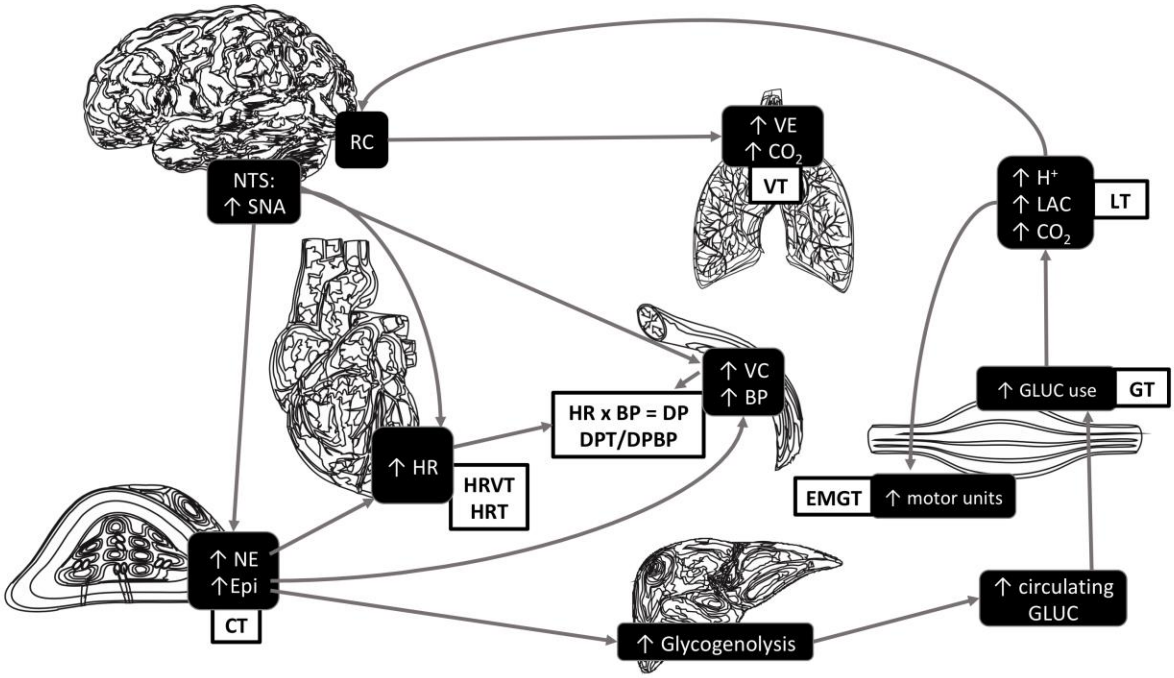
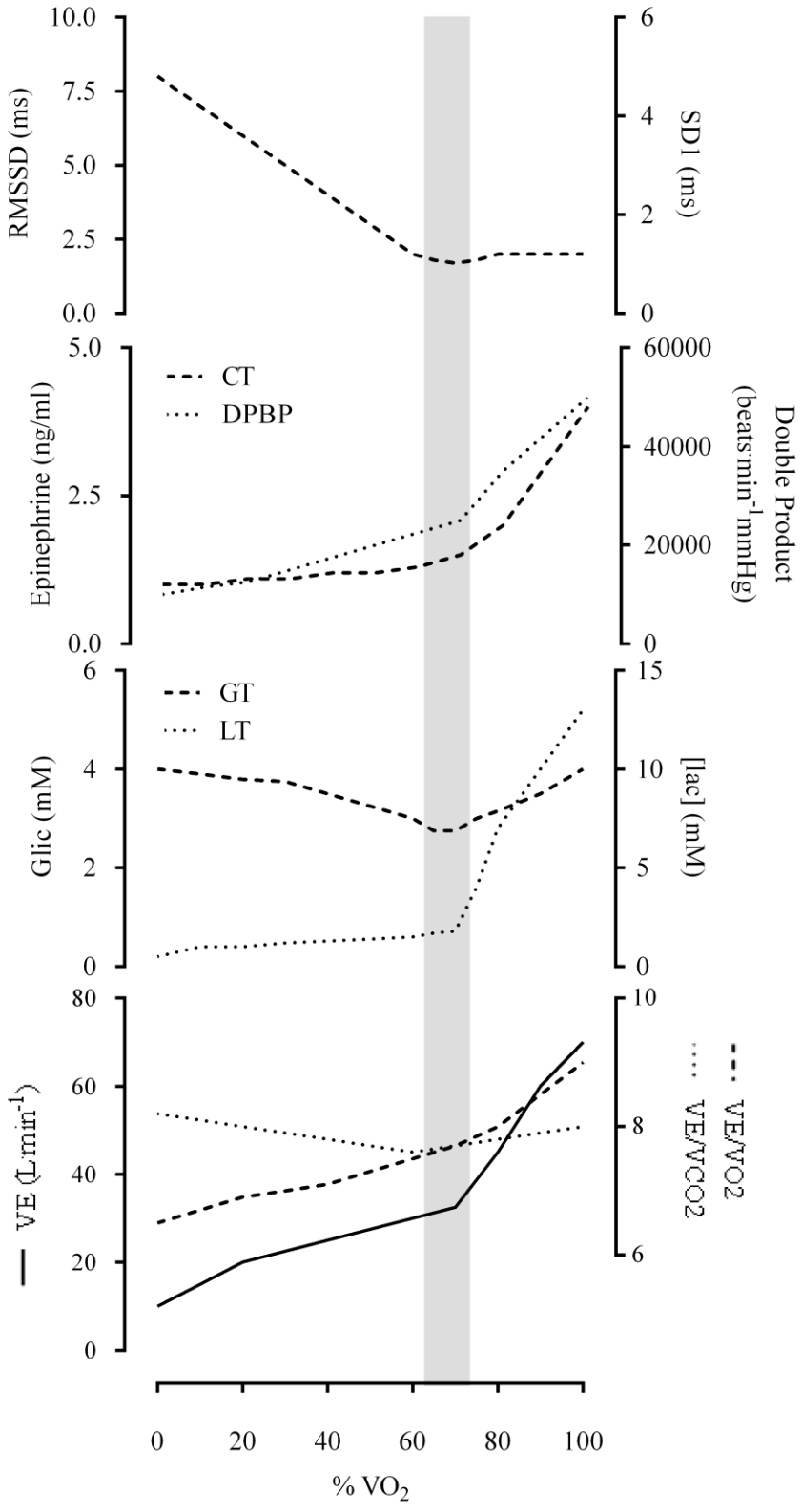


Figure 2



Highlights

- Low-cost and high application methods to identify the anaerobic threshold.
- It is possible to identify the anaerobic threshold regardless the population.
- Individual method for aerobic exercise prescription.